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FINAL TECHNICAL REPORT

July 1 - August 31, 1962

John P. Lawler
Wilbert H. Schlimmeyer
Marvin L. Granstrom

RUTGERS - THE STATE UNIVERSITY
College of Engineering
New Brunswick, New Jersey

EVALUATION AND DEVELOPMENT OF A RATIONAL THEORY
FOR THE
DESIGN OF SEWAGE STABILIZATION PONDS

DA-49-193-MD-2317

Qualified Requestors May Obtain Copies Of This Report From ASTIA

SECURITY CLASSIFICATION
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ABSTRACT

1. Preparing Institution: RUTGERS - THE STATE UNIVERSITY
College of Engineering
New Brunswick, New Jersey
2. Title of Report: Evaluation and Development of a Rational
Theory for the Design of Sewage Stabilization
Ponds.
3. Principal Investigator: Marvin L. Granstrom, Ph.D.
4. Number of pages - 53; illustrations - 16; and
date - January 30, 1963.
5. Contract Number: DA-49-193-MD-2317
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U. S. Army Medical Research and Development Command
Department of the Army
Washington 25, D. C.

The purpose of this study was to evaluate a method suggested for the design of sewage oxidation ponds. The suggested method appeared to be not applicable when tested by a large amount of operational data. This writer proposes that oxidation ponds are usually oversized and that beyond some detention time, or below some loading value termed "critical loading value," the biological activity of the pond is primarily self-perpetuating and cyclic, and does not serve to reduce BOD or coliform bacteria. It is suggested that operational experience be considered in light of this concept to lead to a uniform and systematic accounting of the performance of oxidation ponds. A brief discussion of the problem of odors due to anaerobiasis is included.

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EVALUATION AND DEVELOPMENT OF A RATIONAL THEORY
FOR THE
DESIGN OF SEWAGE STABILIZATION PONDS

The work reported herein was made possible by a Research Contract No. DA-49-193-MD-2317 between Headquarters, U. S. Army Medical Research and Development Command, Office of the Surgeon General and Rutgers, the State University. The study was conducted by Professors W. H. Schlimmeyer, J. P. Lawler, and M. L. Granstrom of Rutgers University. The latter served as Project Director. The period of the contract was 1 July through 31 August 1962.

I. INTRODUCTION

In recent years there has been an expanding interest in the use of a simple detention basin as part of, or as a complete sewage treatment facility. Such a facility has been termed oxidation pond or stabilization pond. The former will be used in this report. The detention periods commonly used vary from tens to hundreds of days.

The designs that have been used are primarily empirical in nature but several attempts have been made in the recent past to suggest appropriate parameters for the actual design of oxidation ponds. With respect to structure most writers suggest that: the pond be enclosed by a dike, inflowing surface water be excluded, the top of the dike be at least eight feet wide to allow machine operation, the waterside slope be 3 or 4 to one, the dike should be planted with grasses to provide erosion protection and to prevent growth of deep rooted plants and weeds, the interior bank of the

dike could be paved to prevent erosion and where seepage is excessive the bottom and sides could be sealed, and the bottom should be essentially level and cleaned of vegetation prior to putting the pond in operation. There seemed to be some variation in suggested inlet and outlet structures. The simplest inlet structure proposed and used is a horizontal pipe discharging horizontally at a point approximately in the center or at least 200 feet from any bank in the pond. Other suggestions were that the inlet structure be similar to those commonly found in a settling tank. The outlet structure might be an overflow weir with, in cases where level control is desired, and it usually is, some arrangement for selection of effluent at different depths. Furthermore, the effluent should come from a level several inches below the surface of the water to prevent excessive algae carryover.

Hermann and Gloyna⁽¹⁾ have suggested a formula for the computation of volume of a lagoon for a given loading as follows:

$$V = 5.37 \times 10^{-8} n q y^{1.07235-T}$$

V = acre feet

N = population equiv.

q = gpcd

y = 5 day-20° BOD

T = operating temp., °C.

Also, in another paper⁽²⁾ they suggest that BOD loadings in lbs/acre/day in the climatic regions similar to Austin, Texas be based partially on the final disposition of the effluent as follows: as land irrigation water, 200; into a diluting stream, 150; and into

an intermittent stream, 50. They further suggested that: the depth vary from two to three-and-one-half feet, intra-pond recirculation was not warranted, ponds should operate in series or in parallel, the influent be evenly distributed across the end of the pond and several outlets be provided.

Oswald, Gotaas., Golueke, and Kellen⁽³⁾ developed design equations to allow determination of volumes and depths necessary to maintain aerobic conditions, at least at the upper depths of the pond, with appropriate consideration of the available light intensity and strength of the waste. They considered an oversized pond to be possibly inefficient because an excess of oxygen production by algae would raise the pH too high for good biological activity.

Neel et. al⁽⁴⁾ have suggested for ice-free locations that allowable BOD loadings in lbs/acre/day could be computed by dividing the lowest monthly average of langley's by two. A langley is defined as a gram calorie/sq. cm. of incident radiation. They listed the low-monthly average of langley's at a number of cities in this hemisphere.

A most significant paper by Marais and Shaw entitled "A Rational Theory for the Design of Sewage Stabilization Ponds in Central and South Africa" has been developed in the recent past⁽⁵⁾. Their paper is divided into five sections. In section I the fundamental differential equation governing the concentration of BOD and faecal bacteria in a pond is derived. Various solutions of equations are given and the relationship between the kinetic activity of a

river and a series of ponds is established. In section II experimental evidence is presented to verify and to indicate the limitations of the theory. In section III criterion within the framework of the theory is developed to determine the maximum loading on an aerobic pond before anaerobic conditions develop. In section IV the theory is applied for the development of a design procedure for a series of ponds. In section V brief consideration is given to the kinetics of recirculation in ponds. It is believed by this writer that the paper is of importance. The hypotheses and design criteria established are the subjects of this present report.

This present report is divided into four sections. Section I is the introduction. Section II is a presentation and discussion of the data in relationship to the derived equations. The data used in this report came from a variety of sources in the United States. The data considered in this section are the Biochemical Oxygen Demand (B.O.D.), 5 day-20°C., and coliform counts of sewage. Section III includes a discussion of the discrepancies between the hypothesized mathematical model and the actual data. A suggestion is made for an alternative mathematical model. Section IV consists of some suggestions on areas for future studies.

II. EVALUATION OF METHOD OF MARAIS AND SHAW⁽⁵⁾.

By assuming that: (1) stabilization pond contents are completely mixed, (2) decomposition or die-away follow first-order kinetics, (3) daily average values of flow and of concentration are sufficiently accurate, and (4) that evaporation can be ignored, Marais and Shaw derived Equation 1. (Also derived as Equation (A3f))

in the Appendix of this report)

$$C = \frac{C_1}{\bar{k}T+1} \quad \text{or} \quad \frac{C_1}{C} = \bar{k}T+1 \quad (1)$$

in which

C_1 = concentration or number in influent flow

C = concentration or number in pond contents

and consequently in effluent flow

T = detention time

\bar{k} = reaction velocity coefficient for a first-order reaction

This equation was used by them as an appropriate mathematical model to describe stabilization pond kinetics.

They collected considerable bacterial count data over periods of months from several ponds in Pretoria, South Africa and in Northern Rhodesia. The bacteria counts included total coliforms, *E. coli* and *F. streptococci*. The data was plotted as the ratio of the initial number of organisms to the observed number, (C_1/C), at some time later (detention time) as the ordinate and detention time as abscissa. According to Equation (1) above, the data should describe a straight line with an intercept of unity and a slope equal to \bar{k} . There appeared to be quite a scatter of points; however they drew the straight lines and values for \bar{k} were taken as follows:

Total coliform	$\bar{k} = 2.13 \text{ day}^{-1}$
<i>E. coli</i>	2.14 "
<i>F. strep</i>	2.82 "

For purposes of design \bar{k} was taken as 2.0. The design equation was then

$$N_0/N = 2.0 T + 1$$

in which N_0 = initial count
 N = count at time T
 T = time, days

Similarly Marais and Shaw collected B.O.D. (5 day-20°C) data from several ponds in South Africa, N. Rhodesia, S. Rhodesia and from several pond studies in the United States including those at Mojave⁽⁶⁾, Syracuse⁽⁷⁾, and Fayette⁽⁴⁾. The foreign data was selected from regions (or seasonal periods) in which the climatic conditions were similar to those in Southern Africa. It was intended that the data from ponds in which the change in loading rate and sampling schedules were inadequate would not be included. However, as shown below some of the data from the United States was not very good. The data was taken from ponds that received raw sewage, settled sewage and aqua privy effluents (probably septic tank effluents). The depth of the ponds varied from two to ten feet. Some 45 observations were plotted according to Equation (1) above and the values of \bar{k} determined to be 0.23 day⁻¹ for Southern and Central Africa and 0.17 day⁻¹ for the U. S. data. This writer suggests that if straight lines were drawn to bracket the data, the values of \bar{k} would vary from about 0.06 to 0.4 day⁻¹. By arbitrarily excluding a couple of points the minimum value of \bar{k} could be increased to 0.1 day⁻¹.

One of the major objectives of this present paper is to evaluate the applicability of Equation (1) by determining the constancy of \bar{k} . Or, it is suggested that, if \bar{k} cannot be shown

to be reasonably constant, then the validity of Equation (1) as a mathematical model is to be reconsidered. Accordingly, considerable data were collected (it is believed almost all available and applicable) from various pond studies in the United States. The data is tabulated in Tables 1 through 9 and plotted according to Equation (1) on Figures 1 through 9. The discussion follows.

Data collected at Fayette, Missouri⁽⁴⁾ are presented in Table 1 together with calculated values of \bar{k} based on Equation (1). This data is also plotted on Figure 1. Inspection of these results reveal that overall rate constant \bar{k} :

1. varied from 0.044 to 0.759.
2. was relatively insensitive to temperature variations.
3. varied approximately inversely with detention time.

Data collected at Farmville, Virginia⁽⁸⁾ are presented in Table II together with calculated values of \bar{k} based on Equation (1). This data is plotted on Figure 2. Inspection of these results reveal that the overall rate constant \bar{k} for any single pond:

1. varied from 0.00 to 0.135.
2. increased from March to June and decreased during July and August. During September and October the average \bar{k} in ponds A and C compared favorably with the March to August average.

	<u>Average \bar{k} during March to Aug.</u>	<u>Average \bar{k} during Sept. to Oct.</u>
POND A	0.033	0.039
POND C	0.078	0.092

TABLE I BOD REMOVAL AT FAYETTE, MISS

PERIOD	INFLUENT BOD C _i MG/L	EFFLUENT BOD C - MG/L					CEL					
		CELL 1 ^A	CELL 2 ^B	CELL 3 ^C	CELL 4 ^D	CELL 5 ^E						
1957												
May	254	35	31	38	34	39	0.07					
Jun	314	32	36	50	54	39	0.08					
Jul	279	44	46	37	45	41	0.04					
Aug	266	43	37	53	57	53	0.04					
Sept	308	45	56	57	52	51	0.05					
Oct	280	36	47	55	51	50	0.07					
Nov	266	33	33	44	29	38	0.07					
Dec	310	34	37	43	37	40	0.08					
1958												
Jan	270	27	32	75	71	42	0.12					
Feb	223	28	40	50	63	63	0.09					
Mar	252	31	34	48	57	66	0.09					
Apr	195	31	32	42	42	40	0.07					
May	252	28	33	37	40	51	0.12					
a Cell 1 - depth 2.5 ft, area 0.75 acres, loading L = 20.3 lb/acre/day, average detention												
b Cell 2 - depth 2.5 ft, area 0.75 acres, loading L = 40.5 lb/acre/day, average detention												
c Cell 3 - depth 2.5 ft, area 0.75 acres, loading L = 60.8 lb/acre/day, average detention												
d Cell 4 - depth 2.5 ft, area 0.75 acres, loading L = 81.1 lb/acre/day, average detention												
e Cell 5 - depth 2.5 ft, area 0.75 acres, loading L = 101.3 lb/acre/day, average detention												
<table><tr><th>CELL 1^F</th><th>CELL 2^G</th><th>CELL 3^H</th><th>CELL 4^I</th><th>CELL 5^J</th></tr></table>								CELL 1 ^F	CELL 2 ^G	CELL 3 ^H	CELL 4 ^I	CELL 5 ^J
CELL 1 ^F	CELL 2 ^G	CELL 3 ^H	CELL 4 ^I	CELL 5 ^J								
1958												
Jul	253	23	27	42	22	35	0.71					
Aug	255	39	21	38	26	37	0.34					
Sept	285	51	18	39	38	44	0.31					
Oct	285	61	21	43	33	36	0.29					
Nov	289	51	22	46	37	35	0.34					
Dec	286	58	25	51	43	38	0.29					
1959												
Jan	267	69	25	55	48	51	0.19					
Feb	272	77	40	67	52	54	0.19					
Mar	243	55	36	66	51	56	0.22					
Apr	247	47	30	49	52	52	0.22					
f Cell 1 - depth 2.5 ft, area 0.75 acres, loading L = 120 lb/acre/day, average detention												
g Cell 2 - depth 2.5 ft, area 0.75 acres, loading L = receives effluent from Cell 3, a												
h Cell 3 - depth 2.5 ft, area 0.75 acres, loading L = 100 lb/acre/day, average detention												
i Cell 4 - depth 5.0 ft, area 1.00 acres, loading L = 60 lb/acre/day, average detention												
j Cell 5 - depth 2.5 ft, area 0.75 acres, loading L = 60 lb/acre/day, average detention												

TABLE I BOD REMOVAL AT FAYETTE, MISSOURI

EFFLUENT BOD C - MG/L				\bar{K} - DAYS ⁻¹				
CELL 2 ^B	CELL 3 ^C	CELL 4 ^D	CELL 5 ^E	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5
31	38	34	39	0.077	0.177	0.210	0.319	0.338
36	50	54	39	0.087	0.153	0.157	0.191	0.349
46	37	45	41	0.048	0.090	0.177	0.187	0.261
37	53	57	53	0.044	0.105	0.102	0.124	0.170
56	57	52	51	0.055	0.085	0.125	0.186	0.239
47	55	51	50	0.075	0.109	0.135	0.198	0.253
33	44	29	38	0.079	0.159	0.170	0.368	0.339
37	43	37	40	0.093	0.170	0.214	0.339	0.388
32	75	71	42	0.111	0.182	0.096	0.138	0.333
40	50	63	63	0.090	0.118	0.134	0.130	0.163
34	48	57	66	0.093	0.167	0.166	0.178	0.183
32	42	42	40	0.076	0.147	0.157	0.209	0.279
33	37	40	51	0.117	0.195	0.256	0.310	0.289

.75 acres, loading L = 20.3 lb/acre/day, average detention time T = 87 days
.75 acres, loading L = 40.5 lb/acre/day, average detention time T = 44 days
.75 acres, loading L = 60.8 lb/acre/day, average detention time T = 29 days
.75 acres, loading L = 81.1 lb/acre/day, average detention time T = 22 days
.75 acres, loading L = 101.3 lb/acre/day, average detention time T = 17 days

CELL 2 ^G	CELL 3 ^H	CELL 4 ^I	CELL 5 ^J					
27	42	22	35	0.759	--	0.296	0.135	0.215
21	38	26	37	0.382	--	0.336	0.113	0.203
18	39	38	44	0.316	--	0.371	0.083	0.189
21	43	33	36	0.253	--	0.331	0.098	0.239
22	46	37	35	0.322	--	0.311	0.087	0.250
25	51	43	38	0.271	--	0.271	0.072	0.225
25	55	48	51	0.198	--	0.227	0.058	0.146
40	67	52	54	0.175	--	0.173	0.054	0.139
36	66	51	56	0.236	--	0.158	0.048	0.115
30	49	52	52	0.294	--	0.238	0.048	0.129

.5 acres, loading L = 120 lb/acre/day, average detention T = 14.5 days
.75 acres, loading L = receives effluent from Cell 3, average detention T > 34 days
.75 acres, loading L = 100 lb/acre/day, average detention T = 17 days
.00 acres, loading L = 60 lb/acre/day, average detention T = 78 days
.75 acres, loading L = 60 lb/acre/day, average detention T = 29 days

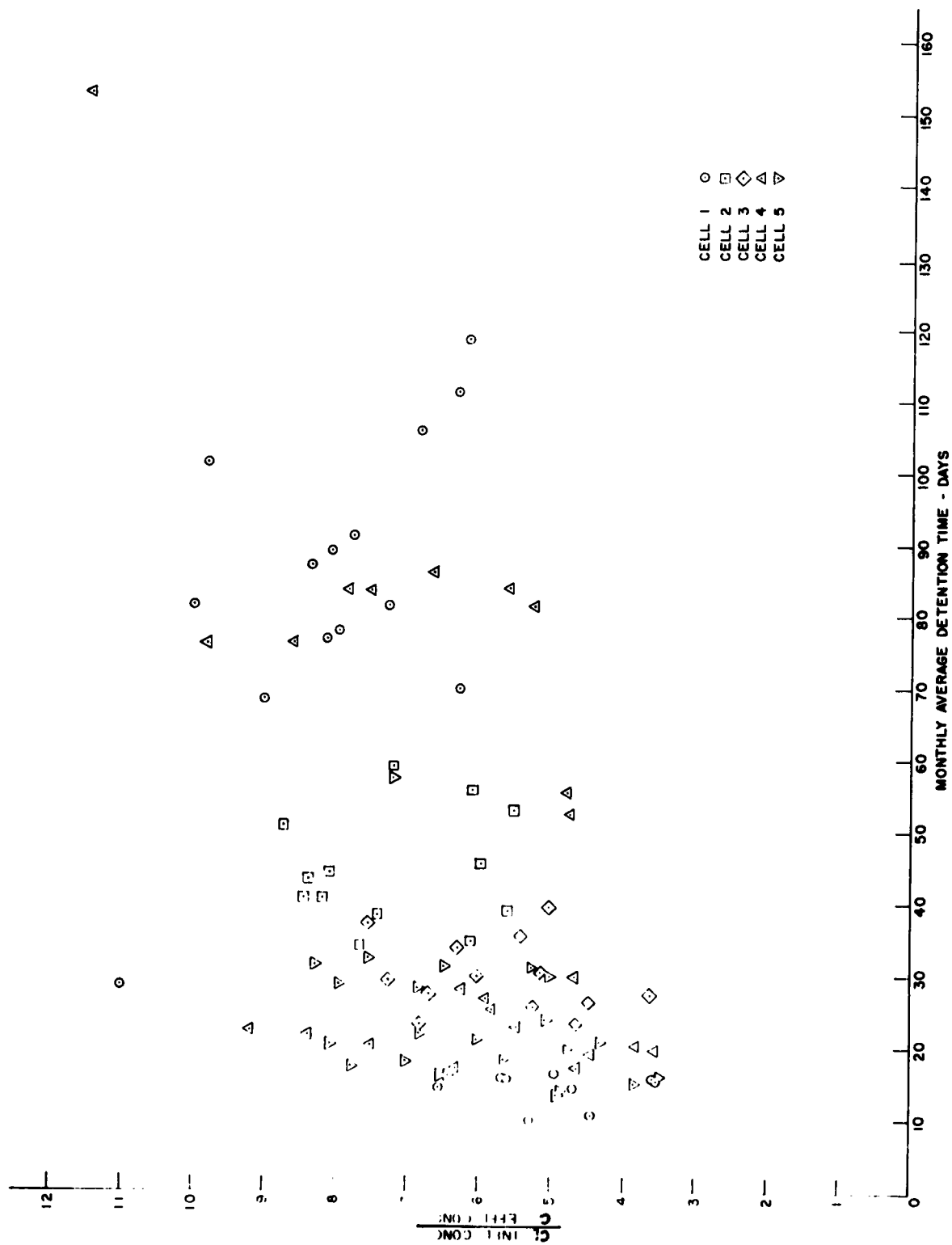


FIGURE 1 BOD REMOVAL AT FAYETTE, MISSOURI

TABLE II BOD REMOVAL AT FARMVILLE, VIRGINIA

PERIOD	INFLUENT BOD Ci A MG/L	EFFLUENT BOD CA - MG/L				K - DAYS ⁻¹		
		POND A ¹	POND B ²	POND C ³	POND A	POND B	POND C	
1959								
March	150	57	69	40	0.013	0.018	0.063	
April	175	43	78	49	0.023	0.019	0.058	
May	172	25	33	41	0.045	0.064	0.073	
June	220	27	34	38	0.054	0.083	0.109	
July	215	40	41	40	0.053	0.064	0.099	
August	195	39	43	52	0.030	0.054	0.063	
	1. Pond A - depth 3 ft, area 1.4 acres, loading L = 11 lb/acre/day, detention time T = 132 days							
	2. Pond B - depth 3 ft, area 1.4 acres, loading L = 21 lb/acre/day, detention time T = 66 days							
	3. Pond C - depth 3 ft, area 1.4 acres, loading L = 32 lb/acre/day, detention time T = 44 days							
		POND A ⁴	POND B	POND C ⁵				
September	197	38	38	40	.048	0.00	.135	
October	173	65	32	72	.019	0.12	.048	
	4. Pond A and Pond B in series - depth 3 ft, area 2.8 acres, loading L = 16 lb/acre/day, detention time T = 176 days							
	5. Pond C - depth 3 ft, area 1.4 acres, loading L = 48 lb/acre/day, detention time T = 29 days							

a. Monthly averages are based on four to five weekly averages each month.

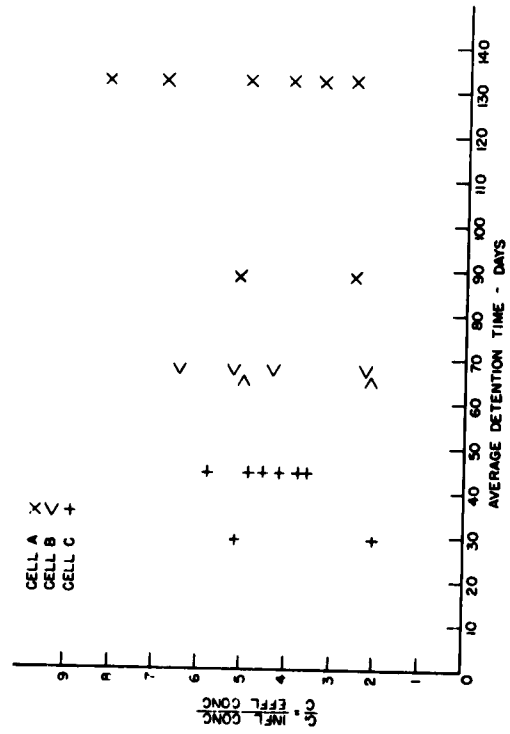


FIGURE 2 BOD REMOVAL AT FARNVILLE, VIRGINIA

TABLE III BOD REMOVAL IN WISCONSIN OXIDATION PONDS

PERIOD	% REMOVAL OF BOD	\bar{k}	AVERAGE DEPTH D FT.	LOADING L LB/ACRE/DAY	DETENTION TIME T DAYS
Junction City I and II					
10/15/57	92.4	0.067	3.5	3.5	180.3
8/19/58	97.2	0.183	↓	8.7	189.6
3/3/59	64.1	0.012		44.0	147.7
7/21/59	98.7	1.355		208.0	56.1
New Auburn					
4/8/58	67.7	0.016	5.0	12.2	132.9
8/19/58	88.3	0.025	5.0	18.7	299.5
Spooner					
12/10/57	67.2	0.011	5.0	24.0	194.0
8/11/58	80.7	0.055	5.0	25.5	119.5

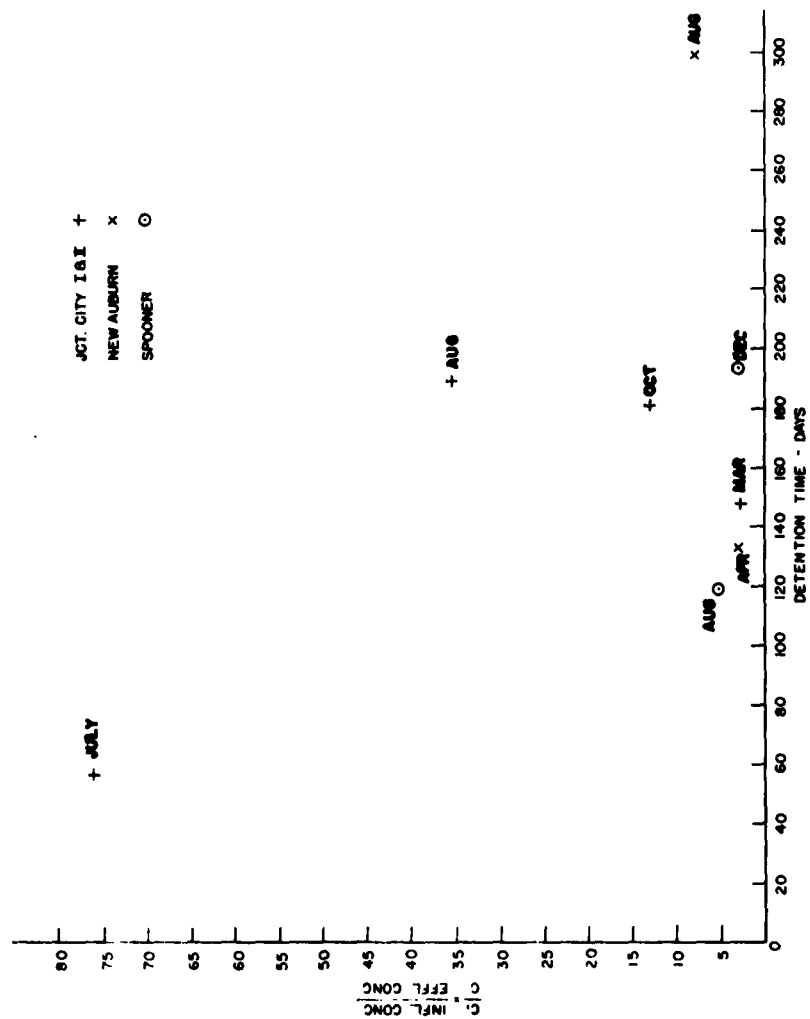


FIGURE 3 BOD REMOVAL IN WISCONSIN OXIDATION PONDS

TABLE IV BOD REMOVAL IN PILOT PLANT OXIDATION PONDS AT SYRACUSE, NEW YORK

BASIN NO.	% REMOVAL OF BOD	\bar{K}	LOADING L LB/ACRE/DAY	DETENTION TIME T DAYS	BASIN NO.	% REMOVAL OF BOD	\bar{K}	LOADING L LB/ACRE/DAY	DETENTION TIME T DAYS
FALL 1958 (6 weeks)					SUMMER 1959 (2 weeks)				
1 ^a	56.1	0.217	135.0	5.9	1	0.0	-	312	3.0
2 ^b	75.5	0.261	↓	11.8	2	51.1	0.175		6.0
3 ^c	72.5	0.155		23.6	3	32.8	0.041		12.0
4 ^d	68.3	0.183		11.8	4	41.2	0.039	104	12.0
5 ^e	66.1	0.166		11.8	5	33.6	0.085	312	6.0
SPRING 1959 (4 weeks)					SUMMER 1959 (2 weeks)				
1	52.3	0.122	72.9	9.0	1	50.0	0.222	208	4.5
2	52.6	0.062	↓	18.0	2	84.6	0.612		9.0
3	49.4	0.027		36.0	3	69.4	0.126		18.0
4	47.9	0.048		18.0	4	55.0	0.068	104	18.0
5	44	0.044		18.0	5	62.4	0.184	208	9.0
SPRING 1959 (4 weeks)					SUMMER 1959 (2 weeks)				
1	34.0	0.115	149.0	4.5	1	44.5	0.089	104	9
2	44.7	0.090	↓	9.0	2	84.3	0.299		18
3	46.3	0.048		18.0	3	85.4	0.162		36
4	47.4	0.050		18.0	4	71.9	0.142		18
5	19.8	0.028		9.0	5	31.4	0.026		18
SPRING 1959 (2 weeks)					a. Basin 1 - 2 ft deep b. Basin 2 - 4 ft deep with baffles c. Basin 3 - 6 ft deep d. Basin 4 - 4 ft deep e. Basin 5 - 4 ft deep				
1	23.6	0.103	238.0	3.0					
2	61.1	0.264		6.0					
3	32.3	0.040		12.0					
4	43.7	0.043	72.9	18.0					
5	29.5	0.070	238.0	6.0					

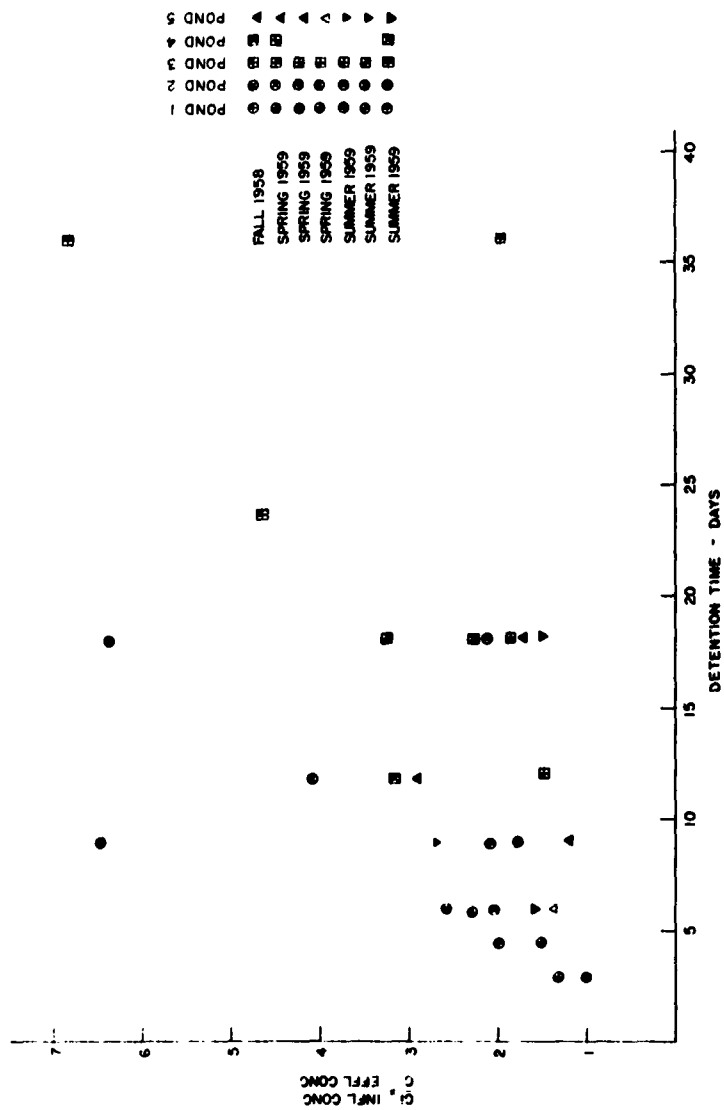


FIGURE 4 BOD REMOVAL IN PILOT PLANT OXIDATION PONDS
AT SYRACUSE, NEW YORK

TABLE V BOD REMOVAL IN SYRACUSE PILOT PLANT OXIDATION PONDS
AFTER SEASONAL ACCLIMATION

BASIN NO.	% REMOVAL OF BOD	\bar{k}	LOADING L LB/ACRE/DAY	DETENTION TIME T DAYS	BASIN NO.	% REMOVAL OF BOD	\bar{k}	LOADING L LB/ACRE/DAY	DETENTION TIME T DAYS	LOADING L LB/ACRE/DAY	\bar{k}	% REMOVAL OF BOD	DETENTION TIME T DAYS
1	44.5	0.092	104	9.0	1	82.5	2.36	467	2.0				
2	84.3	0.298	↓	18.0	2	96.3	6.26	↓	4.0				
3	85.4	0.160	↓	36.0	3	91.2	1.30	104	8.0				
4 ^a	71.9	0.142	↓	18.0	4 ^a	86.8	0.361	104	18.0				
5	31.4	0.026	↓	18.0	5	54.0	0.300	467	4.0				
1	62.0	0.362	208	4.5	1	36.5	0.380	624	1.5				
2	59.1	0.160	↓	9.0	2	63.5	0.567	↓	3.0				
3	87.5	0.389	↓	18.0	3	73.7	0.467	↓	6.0				
4 ^a	63.5	0.097	104	18.0	4	30.0	0.024	104	18.0				
5	69.4	0.251	208	9.0	5	34.3	0.173	624	3.0				
1	69.4	0.757	312	3.0	1	20.2	0.333	1248	0.75				
2	94.1	2.67	↓	6.0	2	68.5	1.466	↓	1.5				
3	84.0	0.437	↓	12.0	3	73.0	0.900	↓	3.0				
4 ^a	97.1	1.86	104	10.0	4	66.4	0.110	104	18.0				
5	87.0	1.117	312	6.0	5	49.6	0.653	1248	1.5				

^aLoading held constant at 104 lb BOD/acre/day

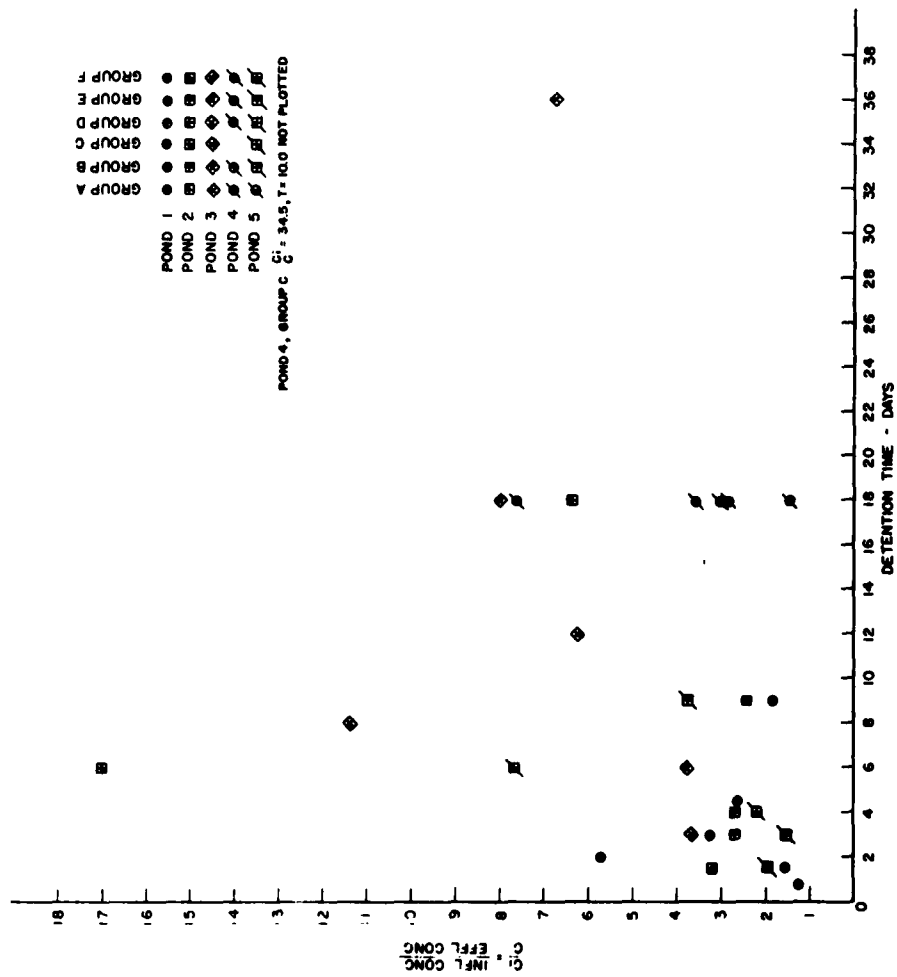


FIGURE 5 BOD REMOVAL IN PILOT PLANT OXIDATION PONDS AT SYRACUSE, NEW YORK

TABLE VI BOD REMOVALS AT MOJAVE, CALIFORNIA

PERIOD 1955 - 1956	INFLUENT BOD C; MG/L	EFFLUENT BOD C MG/L	\bar{K} DAYS ⁻¹	AVERAGE DEPTH D FT.	LOADING L LB/ACRE/DAY	DETENTION TIME T DAYS
EAST POND AS PRIMARY						
Sep 27-Oct 28	195	46	0.39	4	258	8.3
NEW POND						
Nov 28-Jan 16	218	80	0.25	9	590	7
Jan 16-Feb 20	170	69	0.05		109	30
Feb 20-Mar 13	150	57	0.04		66	43
Mar 13-Mar 27	132	51	0.05		89	30
Mar 27-Apr 24	134	52	0.18		280	9
Apr 24-May 15	199	70	0.11		223	17
EAST AS SECONDARY						
Dec 5-Jan 16	80	91	—	4		1.1
Jan 16-Feb 20	69	47	0.10			4.5
Feb 20-Mar 13	57	36	0.09			6.7
Mar 13-Mar 27	51	46	0.05			4.5
Mar 27-Apr 24*	52	49	0.05			1.3
Apr 24-May 15*	70	54	0.13			2.3

*0.01 mg d raw sewage bypassed to this basin

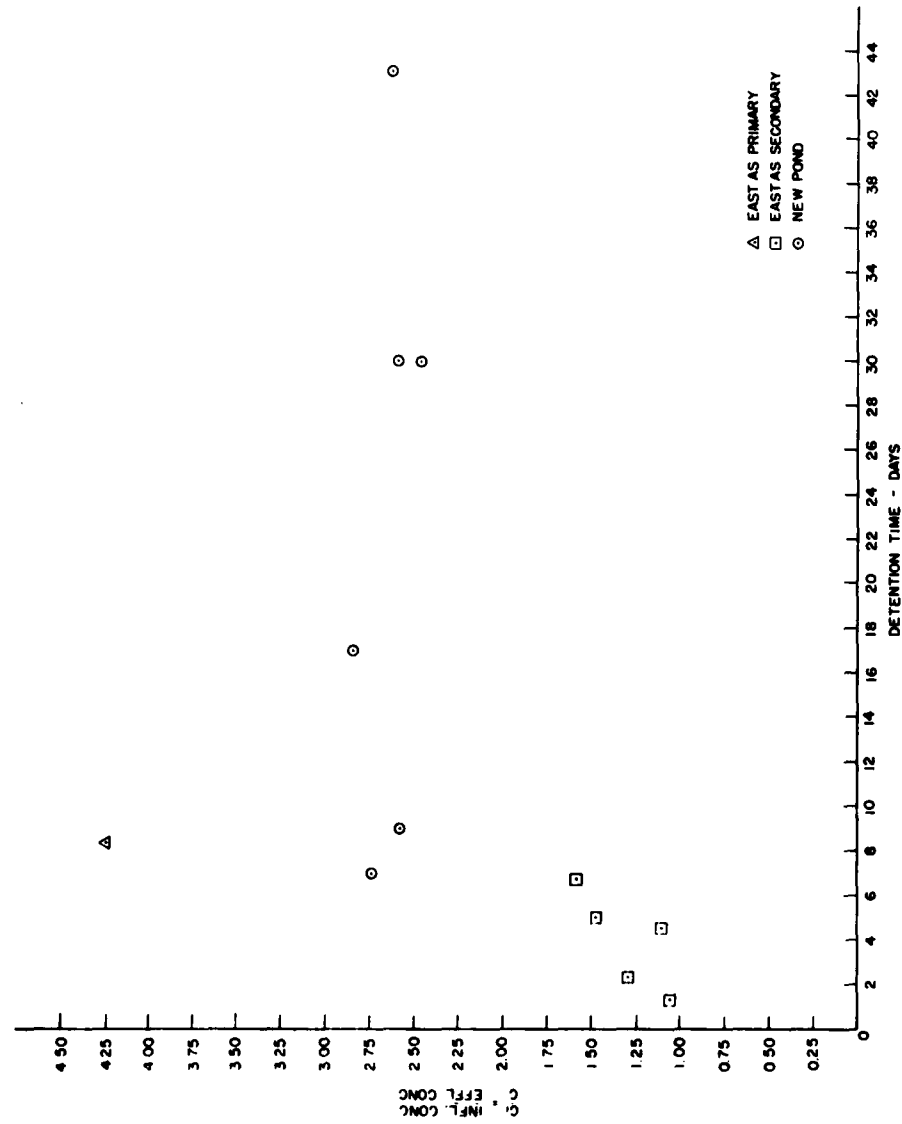


FIGURE 6 BOD REMOVAL AT MOULAVE, CALIFORNIA

TABLE VII BOD REDUCTION AT RICHMOND, CALIFORNIA

PERIOD	INFLUENT BOD C _i MG/L	EFFLUENT BOD C MG/L	DETENTION TIME T DAYS	DEPTH D INCHES	LOADING L LB/ACRE/DAY	\bar{k} - DAYS ⁻¹
POND I						
May 1954	226	43	3	8	136	1.42
Jul 1954	150	12	3	8	93	3.83
Aug 1954	115	23	3	8	71	1.33
May 1956	116	29	30	36	32	0.10
Jul 1956	141	32	20	36	52	0.17
Aug 1956	117	35	10	36	108	0.23
Sept 1956	171	58	5	36	232	0.39
POND II						
Jul 1954	200	46	4	12	115	0.84
Aug 1954	173	19	3	12	153	2.70
Aug 1954	175	28	2	12	231	2.63
Aug 1954	171	84	1	12	440	1.04
POND III						
Aug 1955	200	36	4	14	114	1.14
Aug 1955	153	46	4	14	100	0.58
Aug 1955	121	23	7	24	97	0.61
Aug 1955	147	22	4	24	187	1.42
Jul 1955	117	69	1	24	580	0.70
POND I						
Dec 1953	200	70	3	18	270	1.86
Dec 1953	223	105	1.5	18	610	1.12
Nov 1953	203	59	7	18	115	2.00
Nov 1953	217	50	5	18	177	2.50
Nov 1954	273	90	10	24	106	1.00
Nov 1954	273	79	10	30	129	1.00
Dec 1954	77	39	10	36	137	0.90
Jan 1955	110	54	10	36	133	6.60
Jan 1955	50	26	10	36	89	2.45
Feb 1955	100	13	30	36	28	3.35
POND II						
Nov 1954	266	64	3	12	175	3.15
Nov 1954	988	79	3	12	170	11.49
Dec 1954	361	83	3	12	154	3.36
Jan 1955	140	49	3	12	150	1.86
Feb 1955	147	44	3	12	100	2.34
Feb 1955	91	20	3	12	93	3.54

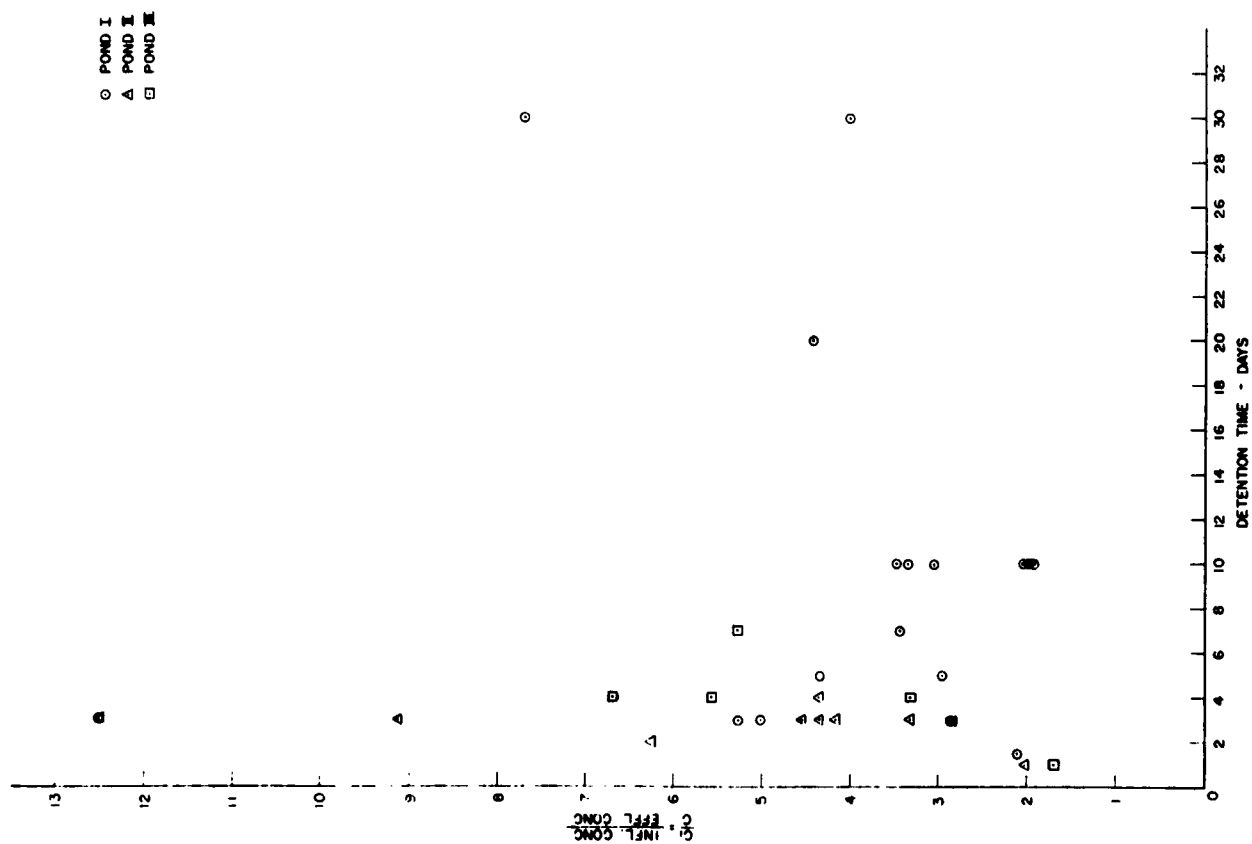


FIGURE 7 BOD REMOVAL AT RICHMOND, CALIFORNIA

TABLE VIII COLIFORM REMOVAL AT FAYETTE, MISSOURI

PERIOD	MPN/100 ML IN RAW SEWAGE $C_i \times 10^{-3}$	MPN/100 ML IN EFFLUENT $C \times 10^{-3}$					$\bar{k} - \text{DAYS}^{-1}$				
		POND 1	POND 2	POND 3	POND 4	POND 5	POND 1	POND 2	POND 3	POND 4	POND 5
1957											
May	23,533	22.0	50.8	—	63.3	52.3	13.1	11.3	—	18.2	27.5
June	38,380	13.6	28.1	38.4	39.5	56.3	27.9	27.0	29.8	36.8	33.7
July	43,500	17.3	27.6	39.5	39.8	41.8	22.4	27.9	29.7	39.3	46.8
August	25,300	18.0	11.6	7.4	16.2	30.8	11.9	36.9	86.7	52.7	34.7
September	31,250	18.8	32.7	19.3	12.3	18.9	15.8	18.1	46.0	96.2	78.3
October	37,100	10.8	13.1	17.8	10.8	17.7	37.8	62.3	68.8	151.4	115.2
November	68,000	6.8	13.5	9.3	14.3	6.3	112.7	113.5	247.0	214.0	610.0
December	68,000	4.0	6.8	6.8	26.2	6.8	195.3	230.0	345.0	119.0	574.0
1958											
January	43,000	4.3	3.6	43.0	43.0	9.3	123.0	293.0	36.9	49.3	284.0
February	—	—	—	—	—	—	—	—	—	—	—
March	48,433	30.1	43.0	53.3	93.0	477.7	20.9	29.3	35.4	27.1	6.5
April	15,767	4.3	6.8	48.7	23.7	9.3	52.7	66.6	13.9	38.2	122.0
May	46,767	6.0	4.3	20.1	26.2	46.8	114.3	319.0	102.6	104.6	73.6
LOADING CHANGED - SEE TABLE I											
July	43,000	3.6	4.3	43.0	0.93	4.3	419	—	—	304	174.9
August	45,825	16.4	1.6	5.5	2.3	4.7	196.5	—	—	263	343
September	172,000	7.6	0.59	6.0	4.06	5.9	1449	—	—	511	939
October	361,500	38.6	1.5	16.5	5.9	26.5	656	—	—	806	478
November	277,250	24.9	2.7	37.4	16.4	5.6	713	—	—	202.5	1580
December	45,825	24.9	2.5	37.4	13.3	9.5	114.3	—	—	40.3	150.5
1959											
January	317,666	59.6	4.7	30.1	18.8	30.1	339	—	—	202.5	337
February	205,333	76.3	17.2	59.6	48.4	18.9	175.5	—	—	52.0	356
March	17,200	30.2	17.2	59.6	46.8	17.2	55.2	—	—	66	48.2
April	18,866	31.7	4.3	31.7	59.7	43.0	60.7	—	—	6.0	22.3

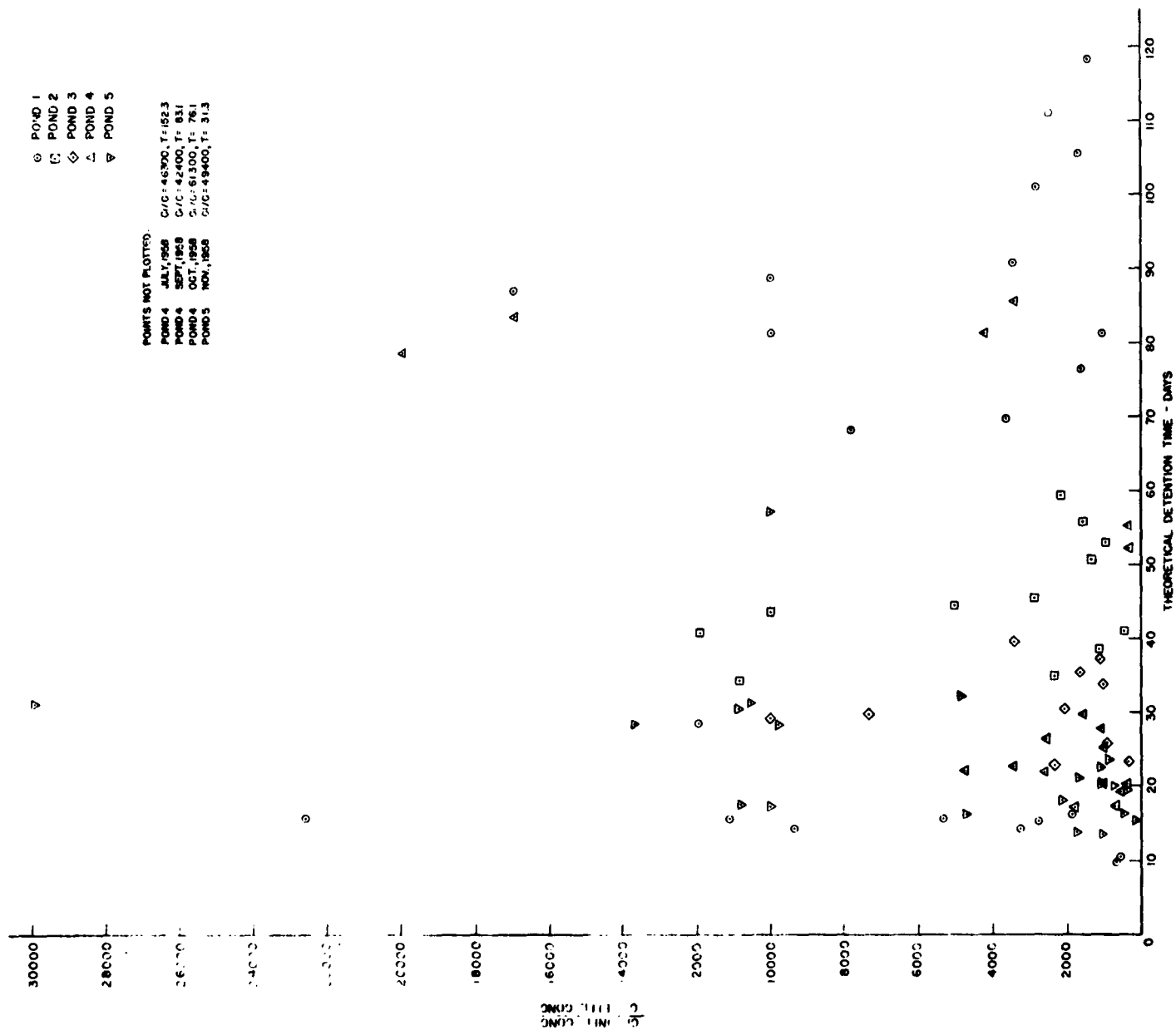


TABLE IX COLIFORM REMOVALS IN AUSTRALIA AND CALIFORNIA

PERIOD	INFLUENT E. COLI. / ML Ci	EFFLUENT E. COLI. / ML C	DETENTION TIME T DAYS	\bar{k} - DAYS ⁻¹
Australia - Murtcaim - Aerobic Pond				
Summer	35,000	3,874	10.5	0.8
Winter	98,750	860	20.0	5.7
Australia - 115E - Aerobic Pond				
Summer	51,000	3,100	17.5	0.9
Winter	89,100	3,600	37.0	0.6
Australia - Murtcaim - Anaerobic Pond				
Summer	125,000	35,000	3.5	0.7
Winter	162,000	53,000	3.5	0.6
Australia - 115E - Anaerobic Pond				
Summer	1.05×10^6	143,000	3.5	1.8
Winter	162,000	89,000	7.0	0.1
California - New Pond				
1955-56				
Nov 28-Jan 16	61,000	30,000	7	0.15
Jan 16-Feb 20	72,000	15,000	30	0.13
Feb 20-Mar 13	35,000	8,300	43	0.08
Mar 13-Mar 27	67,000	13,000	30	0.14
Mar 27-Apr 24	45,000	32,000	9	0.05
Apr 24-May 15	150,000	13,000	17	0.62
California - West Lagoon				
Sept 27-Oct 28	80,000	61,000	1.2	0.26
Oct 28-Jan 16	40,000	24,000	6.9	0.10
Jan 16-Mar 27	60,000	13,000	1.3	2.79
Mar 27-Apr 24	45,000	55,000	2.4	—
Apr 24-May 15	150,000	26,000	1.8	2.65

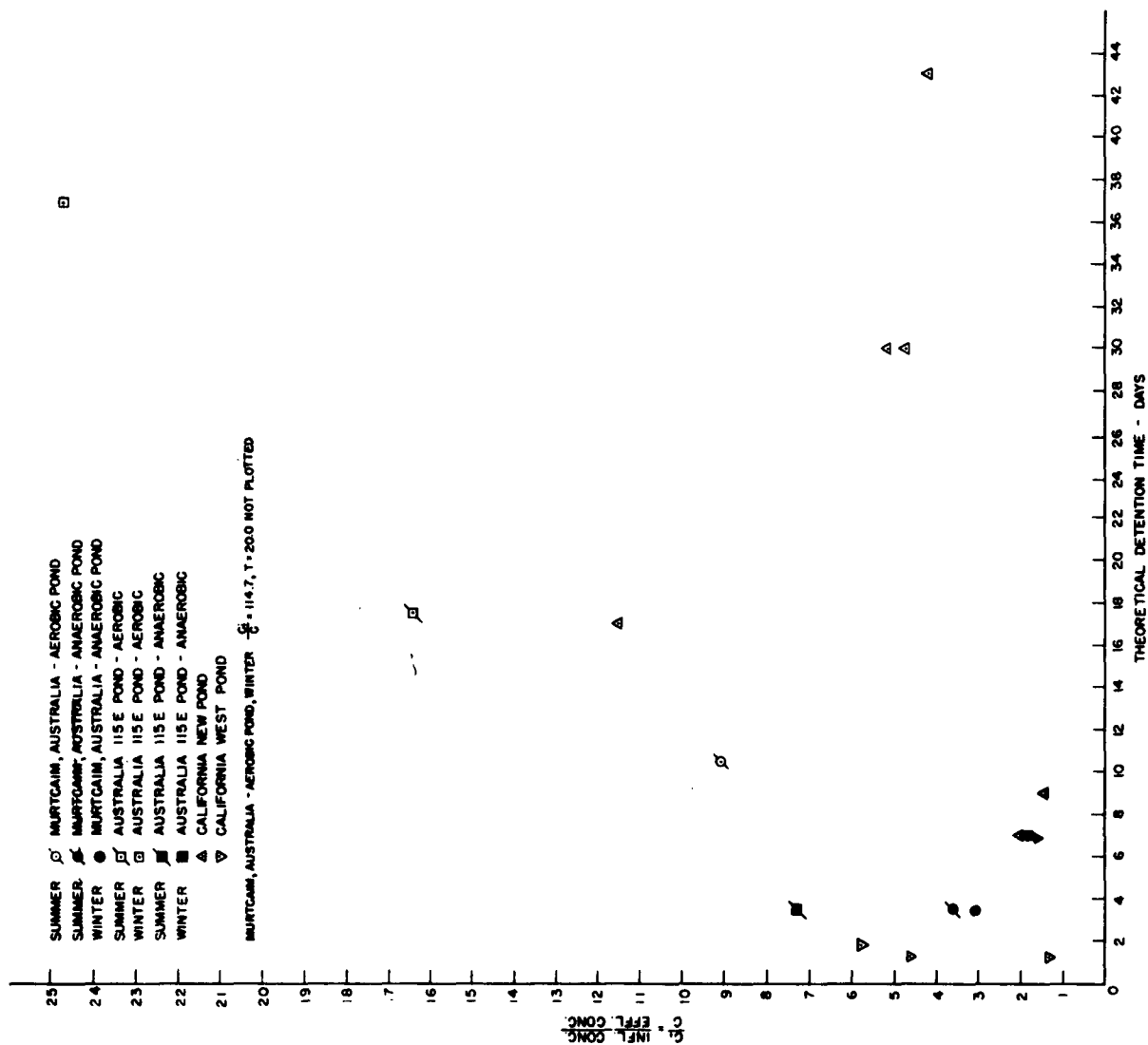


FIGURE 9 COLIFORM REMOVAL IN AUSTRALIA AND CALIFORNIA

The \bar{k} dropped by 60 to 64 per cent from September to October in ponds A and C.

3. varied approximately inversely with detention time.

Data collected during the studies in Wisconsin oxidation ponds⁽⁸⁾ are presented in Table III. Figure 3 is a plot of this data.

The overall rate constant \bar{k} :

1. varied from 0.011 to 1.355.

2. was higher during the summer.

3. did not vary inversely with detention time although a comparison between the New Auburn and Spooner ponds during August revealed that \bar{k} decreased with increasing detention time.

Data collected in pilot plant oxidation ponds at Syracuse⁽⁷⁾ are presented in Table IV and Table V. Figures 4 and 5 are plots of the data. The data shows considerable variation and conclusions are difficult to draw. Part of the variation can be attributed to the small number of samples which were analyzed. Only one or fewer samples were collected each week. Table V describes conditions at Syracuse during the last five weeks of the summer when the loadings were increased weekly from 104 lb.BOD/acre/day to 1248 lb.BOD/acre/day. The variation in \bar{k} was extreme, values varying from 0.026 to 6.26. It is evident that loadings in some basins were changed before equilibrium conditions had been attained. Failure to continue a constant loading for a sufficient period resulted in samples being collected which represented the tail-end of the previous weeks loading.

Data collected at Mojave, California⁽⁶⁾ are found in Table VI and plotted on Figure 6, and data collected at Richmond, California⁽³⁾ in Table VII and Figure 7. At Mojave, the overall rate constant \bar{k} appears to be inversely proportional to detention time with values of \bar{k} ranging from 0.03 to 0.39. At Richmond \bar{k} varied from 0.1 to 3.83 and showed a time relationship only for detention times greater than ten days.

The available data on the removal of coliform organisms in oxidation ponds is more limited than BOD removal data. Data from Fayette, Missouri⁽⁴⁾ is found in Table VIII and plotted on Figure 8. Data from Australia⁽¹⁰⁾ and California⁽⁶⁾ are found in Table IX and plotted on Figure 9. These data showed extreme variation with rate constants varying from 0.05 to 1,449. There was no correlation of coliform reduction and detention time.

Thus it appears upon more extensive evaluation that Equation (1) does not serve very well as a mathematical model to describe the decrease of a waste constituent with time. The data from the several sources reveal generally that the value of \bar{k} varies widely for no readily apparent reason, is not dependent upon temperatures above freezing, and is approximately inversely proportional to detention time. An attempt is made in the succeeding Section to develop another relationship.

III. DISCUSSION OF DISCREPANCIES BETWEEN PROPOSED THEORY AND EXPERIENCE.

It is apparent from the data analysis in section II of this report that the proposed means of evaluating pond performance has

certain deficiencies. It is the purpose of this section of the report to suggest reasons for the apparent deficiencies and to propose another means of evaluation of pond performance.

The commonly used detention periods in stabilization ponds is several times the period normally required for essentially complete biochemical oxidation of the putrescible organic matter in sewage. Because of the biological system in a stabilization pond, the organic matter in the sewage is decomposed by bacterial action and the nutrients released are converted in part to the plankton, primarily algae, and a biological cycle is established -- as the algae die, the bacteria decompose the dead cells releasing nutrients for more algae, etc. The continuous source of energy is the sun, and the continuous sewage additions provides the replacement of dissipated or discharged nutrients. The oxygen released by the photosynthetic processes of the algae are utilized by the bacteria to decompose aerobically the organic matter present. A state of equilibrium may be reached if constant conditions of sewage feed, sunlight, temperature, etc, persist for a period of time. The effluent from such a pond would contain organic matter, to some measure living on dead plankton cells, and if the ordinary means of BOD measurement is used, the decay of these cells in a bottle in the dark would yield an oxygen demand. Depending upon the form or state of the receiving water course or land surface the effect of the living algae cells, which are measured as BOD, may be significantly different than an equivalent amount of BOD in the form of say sewage. However, the BOD is then calculated. (It is not

the purpose of this report to do so, but it might be interesting to try to determine what portion of the BOD of a pond effluent is in the form of plankton cells and what portion is undecomposed sewage,)

It is suggested that changes in the theoretical detention times of a stabilization pond will not result in a corresponding change in the BOD of the effluent. Thus, evaluation of the rate of sewage decomposition by measurement of the effluent BOD and relating those values to the influent BOD may not be as straightforward a procedure as suggested by Marais and Shaw⁽⁵⁾. For example, if say 20 days is sufficient time for a pond to reach a certain value of effluent BOD, increase of the detention time to say 40 days might not, as suggested above, result in a change in effluent BOD. However, the value of \bar{k} will be changed by a factor of approximately two. Or, after a certain minimum detention time in a pond (value not yet determined) increase in detention times would result in a decrease in \bar{k} . This is illustrated in Figures 1-9; if C reaches an equilibrium values, C_1/C is constant and the slope \bar{k} changes with detention time T .

With this concept in mind, the values of \bar{k} determined as the slopes, are plotted vs. detention time T in Figures 10 and 11. It is seen, most clearly on Figure 10, that the data seem to describe a hyperbola - or $\bar{k} T$ might be considered a constant. From Equation (1),

$$C = \frac{C_1}{\bar{k}T+1}, \quad (1)$$

it is seen that if $\bar{k}T$ is a constant, C is a constant fraction of C_1 .

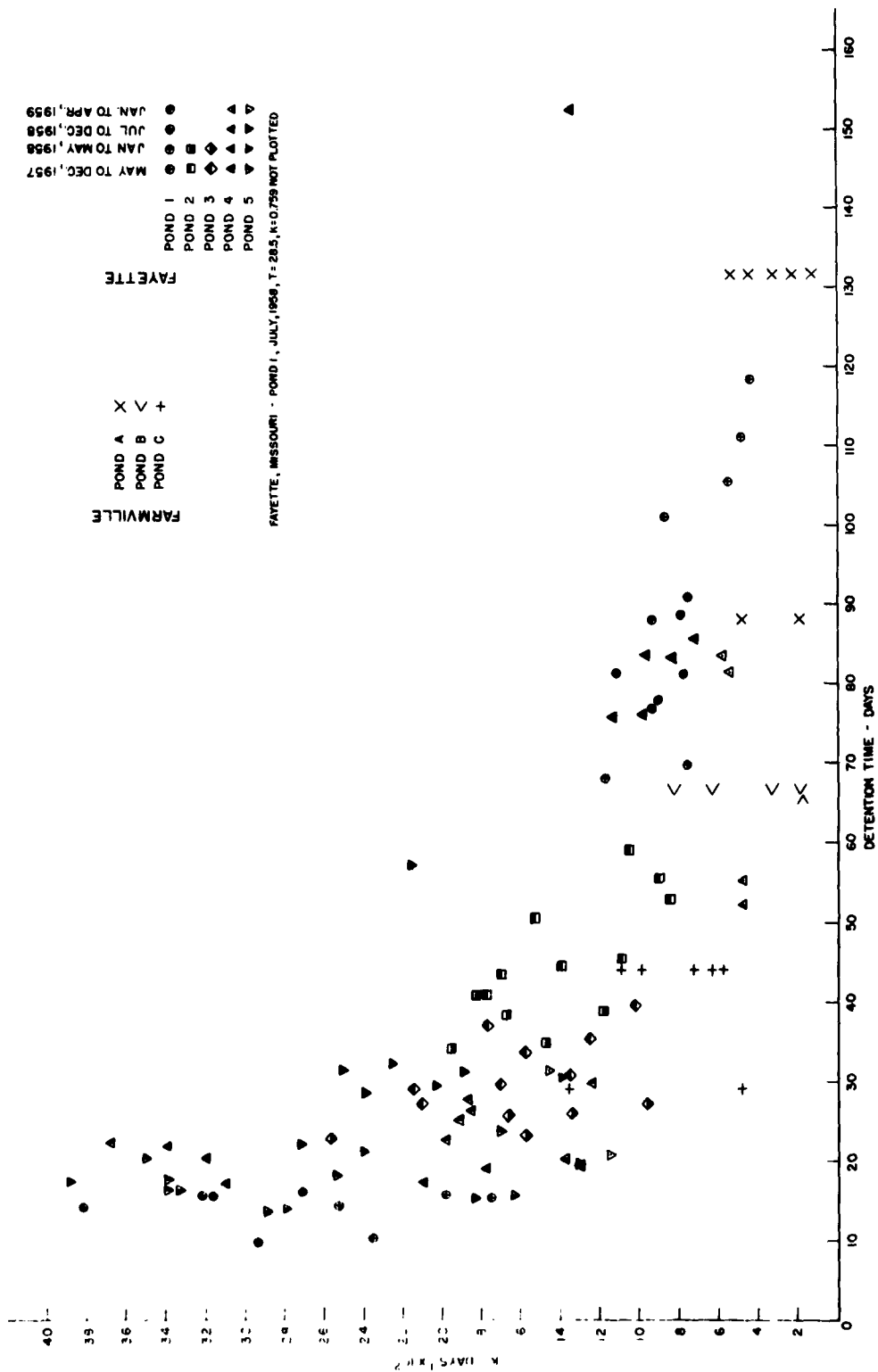


FIGURE 10 BOD REMOVAL RATE CONSTANT VERSUS DETENTION TIME AT FAYETTE, MISSOURI AND FARMVILLE, VIRGINIA

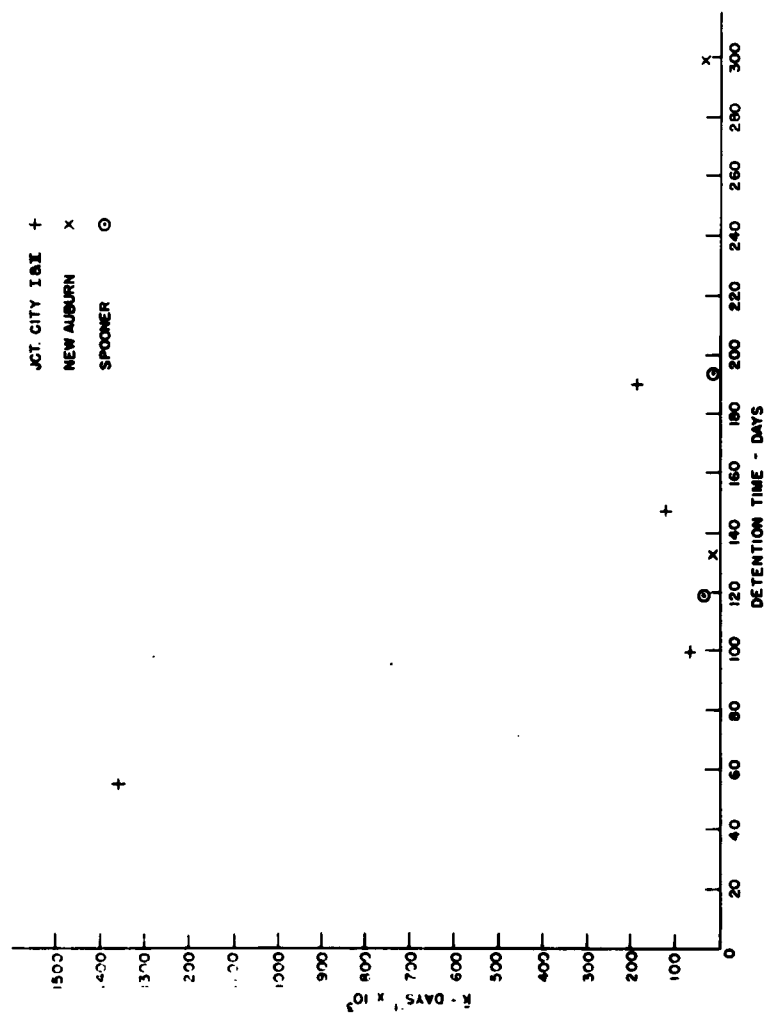


FIGURE 11 BOD REMOVAL RATE CONSTANT VERSUS DETENTION TIME
IN WISCONSIN OXIDATION PONDS

Or, irrespective of detention time the same fraction removal is effected.

To check this assumption, values of BOD removal (\bar{R}) in terms of mg/l/day as shown on Figures 12 - 15. On Figure 12, the plot of the Fayette, Missouri data⁽⁴⁾, the average ratio of \bar{R}/\bar{L} equals approximately 0.85 and the range of detention time, from Figure 1 is 10 to 160 days. This removal efficiency was as effective at the maximum loading rate of about 20 mg/l/day as it was at the lower loading rates. Figure 13 is a plot of the data from the Texas studies⁽¹⁾, the ratio of \bar{R}/\bar{L} has an average value of about 0.9 and the maximum loading is approximately 90 mg/l/day. On Figure 14, the data from the Farmville, Virginia studies⁽⁸⁾, the average value of \bar{R}/\bar{L} is about 0.85. On Figure 15, the data is from the Wisconsin studies⁽⁹⁾, the ratio of \bar{R}/\bar{L} is about 0.80 except at the highest loading when the ratio is 1.0. This last point doesn't seem to have any significance. Thus we see that ratio of \bar{R}/\bar{L} lies in a rather narrow range of 0.80 to 0.90. More significantly, perhaps, is that for a given pond the ratio is very nearly constant, i.e. a straight line seems to represent the data very well. A significant increase in loading rate, over those observed from these data, might result in a break in the line relating \bar{L} to \bar{R} on Figures 12-15. That is, if the efficiency of removal drops the slope of the line would decrease.

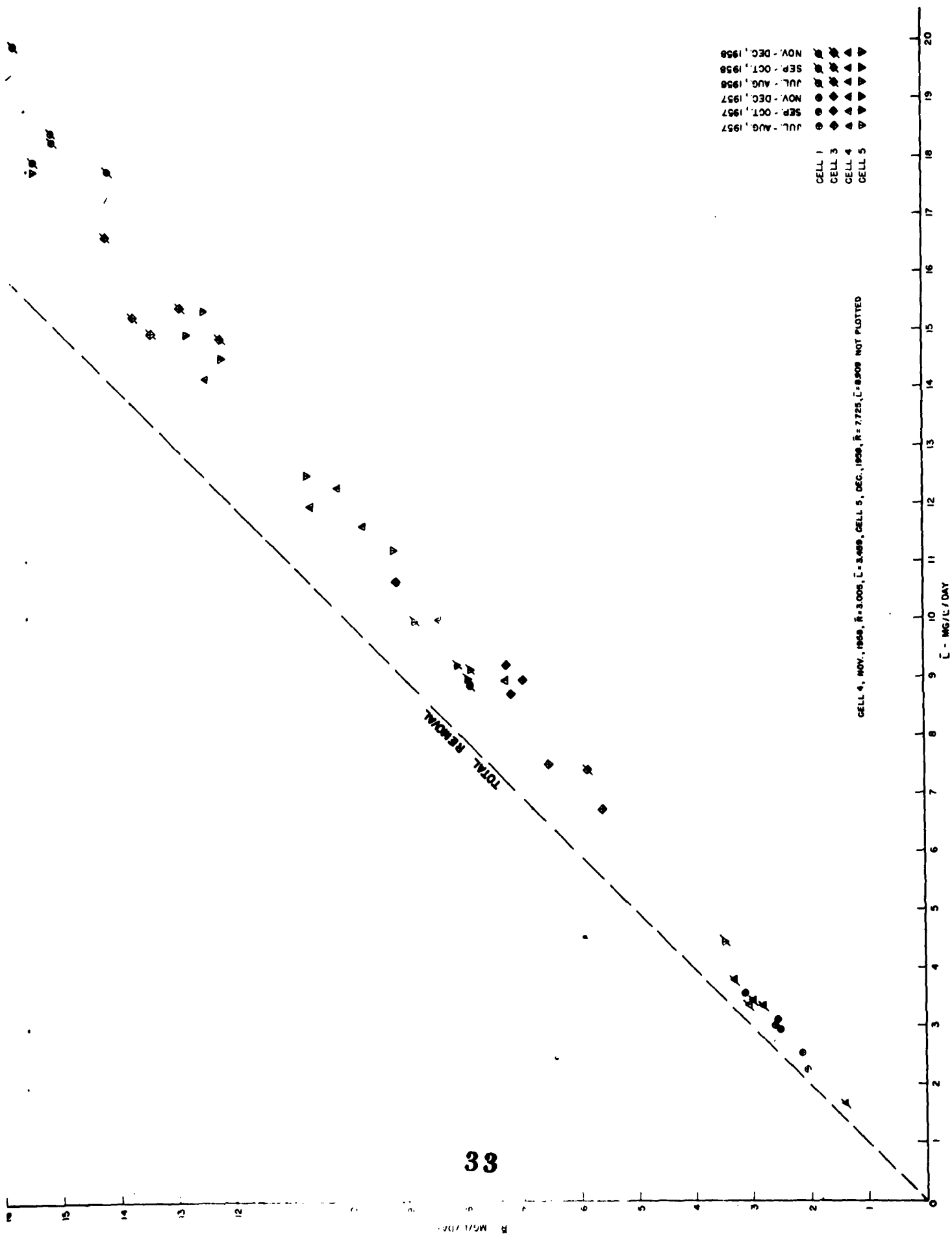


FIGURE 12 BOD REMOVAL VERSUS BOD LOADING AT FAYETTE, MISSOURI

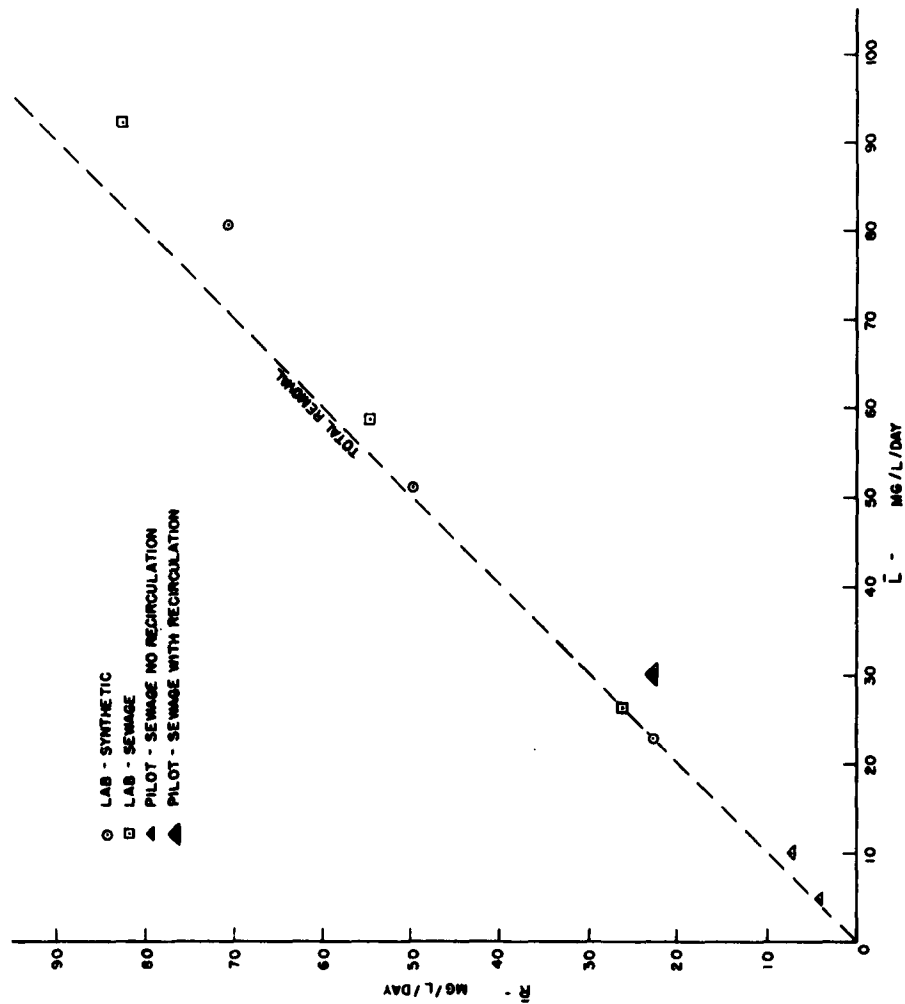


FIGURE 13 BOD REMOVAL VERSUS BOD LOADING IN TEXAS LABORATORY AND PILOT SCALE OXIDATION PONDS

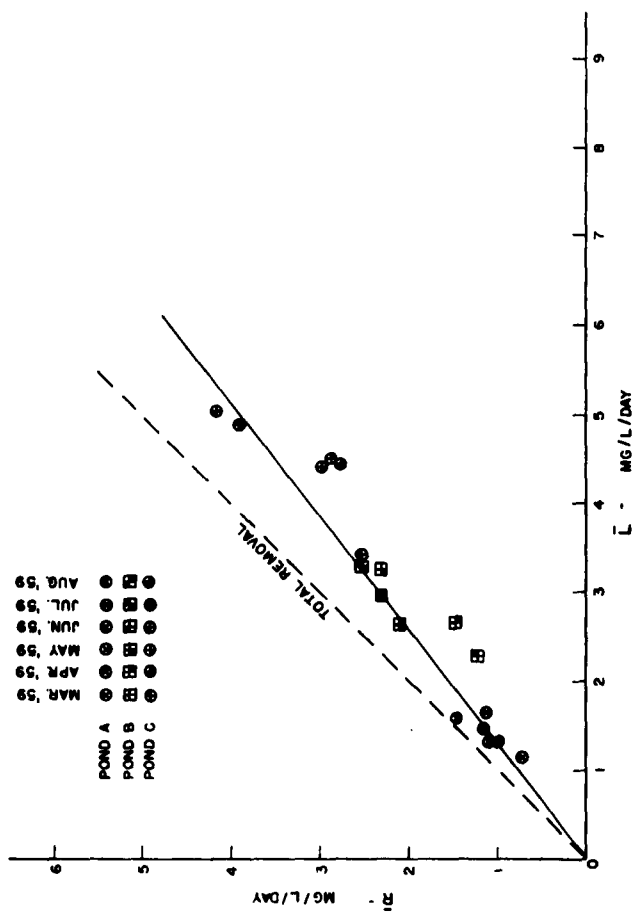


FIGURE 14 BOD REMOVAL VERSUS BOD LOADING AT FARMVILLE, VIRGINIA

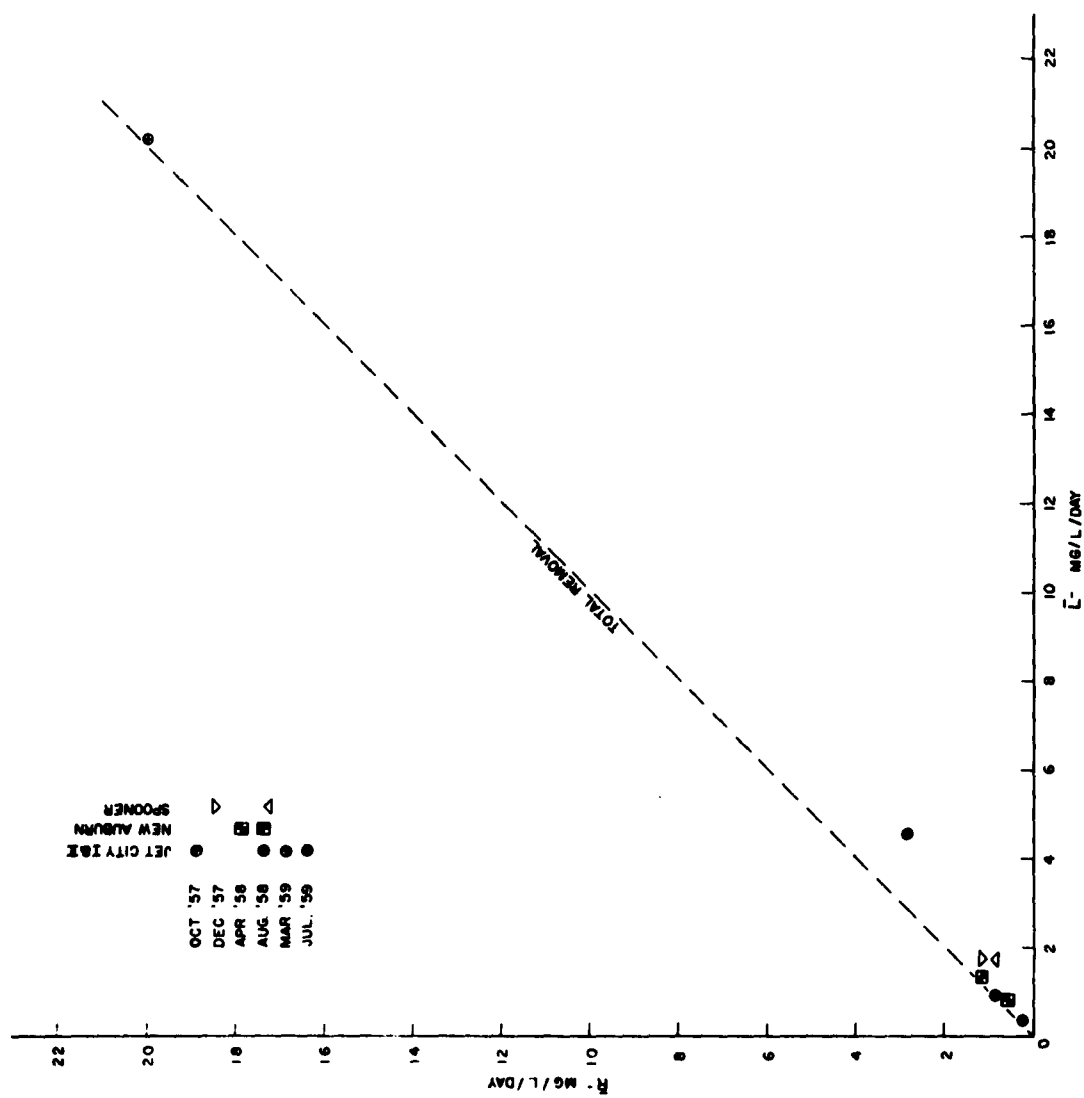


FIGURE 15 BOD REMOVAL VERSUS BOD LOADING AT WISCONSIN

IV. POSSIBLE AREAS FOR FURTHER STUDY.

In section II of this report it was shown that the proposed relationship⁽⁵⁾ between the ratio of incoming to outgoing BOD concentrations or bacteria numbers as a linear function of detention time was not a good representation of the accumulated data. In section III the primary reason for such deviations as noted in section II was proposed; namely that BOD reduction, and possibly reduction in bacteria numbers, were essentially completed in a period of time much less than the detention periods commonly allowed in oxidation ponds. However, there must be an upper limit of loading rate, or reduction in detention time, at which the efficiency of removal is reduced. This is illustrated by Figure 16.

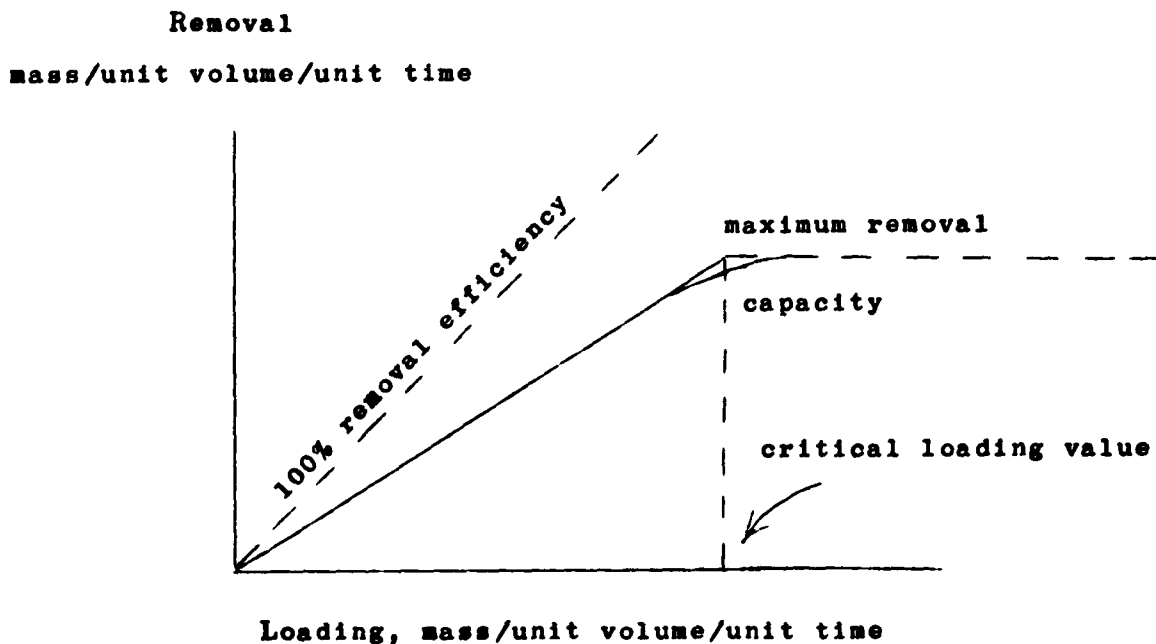


FIGURE 16

Relationship between Loading and Removals in an Oxidation Pond

The rising part of the curve in Figure 16 is illustrated by real data on Figures 12-15. The data available for this study did not reach to the region where the curve flattens out. That is, the critical loading value had not been reached.

If one is primarily interested in removal efficiencies, operation of the pond in any region up to the critical loading value would yield an effluent with a concentration of say 0.1 to 0.2 the concentration of the influent, i.e. $C_1/C = 5$ to 10, or percentage removals are 80 to 90%. In this loading region, i.e. the rising part of the curve, the range of removal efficiencies is due, not to differences in detention time, but rather to differences in conditions such as temperature, pH, presence or absence of essential nutrients, sunlight intensity and duration, degree of cloudiness etc. Some of these above listed conditions vary with the season. Even so, variation in such conditions may have a reasonably small effect on the slope of the rising part of the curve on Figure 16, but might shift the break-off point or critical loading value rather substantially. Determination of which effect would be most likely, i.e. change in slope or location of critical loading value, would be an interesting topic for further study.

The suggestion of single pond removals illustrated by Figure 16 could well apply to ponds in a series. That is, if a second pond could remove say 80-90% of the influent BOD at any loading less than the critical loading value, dividing it up into several ponds in series would lead to significant overall increase in efficiency. Marais and Shaw⁽⁵⁾ have illustrated this concept and many pond designers

have recommended it.

Of course the discussion to this point has not included consideration of the aerobic or anaerobic conditions of the pond. Oswald⁽¹¹⁾ suggests that most operating oxidation ponds are anaerobic or facultative. The latter is anaerobic near the bottom and aerobic near the top. In the anaerobic state good methane fermentation may block reduction of sulfur compounds; thus a state of anaerobiosis does not necessarily result in an odor nuisance, particularly if the top layers of the pond are aerobic. Thus, one cannot dismiss the concept of the critical loading value as a design criteria on the basis that anaerobic conditions might exist. In fact during several hours per year, if not several hours per day, all oxidation ponds might be anaerobic through the entire depth, without creating odor problems.

One additional concern in loading must be discussed, that is the condition of icing. In the northerly regions of the United States and of course other similar climatic regions, an oxidation pond will be frozen over for several days to several months each year. During this time biological decomposition has been slow and organic matter has accumulated. However, due to sedimentation overall removals may be good. Upon warming biological decomposition begins and is probably anaerobic. During this spring breakup period free oxygen made available by photosynthesis or aeration is inadequate to maintain aerobic conditions. The pond or aeration may emanate odors. The greater the accumulation of organic matter, and this is of course related to loading rates, the longer the odor con-

dition will persist. This too might be an interesting area for study.

Thus, it appears that as operating and experimental evidence is accumulated, bases for design may be reconsidered, and this writer suggests that the method of expressing results suggested by Figure 16, that is removals vs. loadings both in terms of mass/unit volume/unit time, may prove to be of value.

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APPENDIX

If a material balance is made over the oxidation pond the word equation yields Equation (A-1).

$$\text{Inflow} - \text{Outflow} + \text{Production} = \text{Accumulation} \quad (\text{A-1})$$

If

$$Q_1 = \text{inflow volumetric rate, (L}^3\text{T}^{-1}\text{)}$$

$$Q_0 = \text{effluent volumetric rate, (L}^3\text{T}^{-1}\text{)}$$

$$V = \text{pond volume } \text{L}^3$$

$$C_1 = \text{inflow concentration (ML}^{-3}\text{)}$$

$$C_L = \text{concentration at any point in the pond (ML}^{-3}\text{)}$$

$$C = \text{effluent concentration (ML}^{-3}\text{),}$$

Equation (1) can be written

$$Q_1 C_1 - Q_0 C - \int_0^V K dV = \frac{d}{dt} \int_0^V C_L dV \quad (\text{A-2})$$

Note that the production term has a negative sign to indicate decrease in waste constituent concentration. "K" represents the rate at which waste constituent concentration is being removed by physical, chemical or biological means and has the units of $\text{ML}^{-3}\text{T}^{-1}$.

Since the reaction rate may depend upon the concentration C_L and since C_L may vary from point to point in the pond, K must be written inside the integral. For the same reason the accumulation term of Equation (A-2), which represents the total change in mass with time, must be written as the derivative of an integral. In fact, all the quantities in Equation (A-2) may vary with time.

Equation (A-2) may be modified for various conditions. Several

different cases are discussed below.

Case 1 - Lagoon Contents Completely Mixed.

The concentration at any point in the pond is equal to the effluent concentration, i.e. $C_L = C$. Equation (A-2) can then be written as

$$Q_1 C - Q_0 C - KV = \frac{d(CV)}{dt} \quad (A-3)$$

Note that the integrals do not appear in Equation (A-3) because the effluent concentration C is a function only of the total volume V and not a function of position within pond.

Case 1-a - Complete Mixing and Constant Volumetric Flow Rate.

If $Q_1 = Q_0$ Equation (A-3) simplifies to Equation (A-3a)

$$Q(C_1 - C) - KV = \frac{dCV}{dt} \quad (A-3a)$$

Case 1-b - Complete Mixing, Constant Mass In Flow Rate, Constant Pond Volume and Steady State.

In this case $dC/dt = 0$ and Equation (A-3) can be written

$$Q(C_1 - C) - KV = 0. \quad (A-3b)$$

If the order of the reaction is known the relationship between time and effluent concentration can be derived. For example, in the case of a concentration reduction in accordance with a first-order reaction,

$$K = kC;$$

so, Equation (A-3b) can be written

$$Q(C_1 - C) - kCV = 0 \quad (A-3c)$$

to yield Equation (A-3c).

By dividing through by V, one obtains

$$\frac{Q}{V} (C_1 - C) - kC = 0. \quad (A-3d)$$

Since $V/Q =$ detention time T , Equation (A-3d) may be written

$$(C_1 - C) = kCT \quad (A-3e)$$

or

$$\frac{C_1}{C} = kT + 1 \quad (A3f)$$

which is also Equation (1) in the body of this report and the working equation derived similarly by Marias and Shaw⁽⁵⁾.

Case 2 - Steady State Conditions, Imperfect Mixing.

If $Q_1 = Q_0$, Equation (A-2) can be written

$$Q(C_1 - C_0) - \int_0^V k dV = 0. \quad (A-4)$$

If only overall conditions are of interest the integral can be replaced by $\bar{R}V$ to yield.

$$Q(C_1 - C_0) - \bar{R}V = 0 \quad (A-4a)$$

or

$$\bar{R} = \frac{C_1 - C_0}{T} \quad (A-4b)$$

\bar{R} is in the removal effected by the pond in terms of mass/unit time/unit volume. Relating \bar{R} to \bar{L} , the loading on the pond, ($\bar{L} = QC_1/V$) may allow evaluation of the pond without knowledge of the degree of mixing, extent of sedimentation, or reaction order. The results of such evaluation of \bar{R} vs. \bar{L} are shown on Figs. 12-15 in the body

of this report.

Incidentally Equation (A-3b) could be obtained from Equation (A-4a) by assuming a zero-order reaction and simply designating \bar{R} as K.

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